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Overview of the Regulatory Baseline, Technical Basis, and Alternative Control Levels for Nitrogen Oxides (NOX) Emission Standards for Small Steam Generating Units

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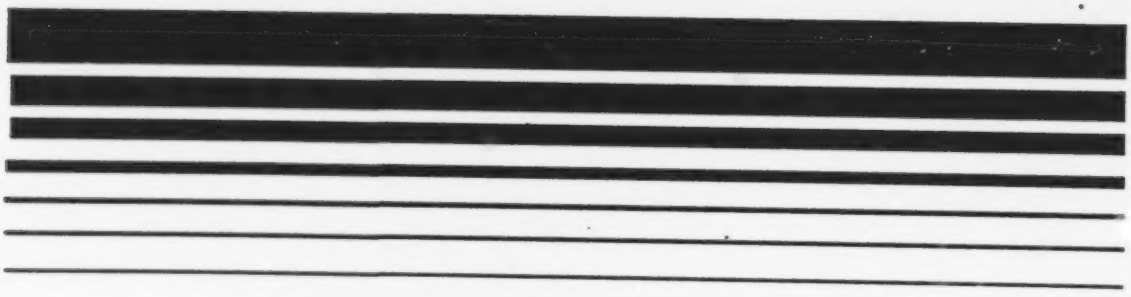

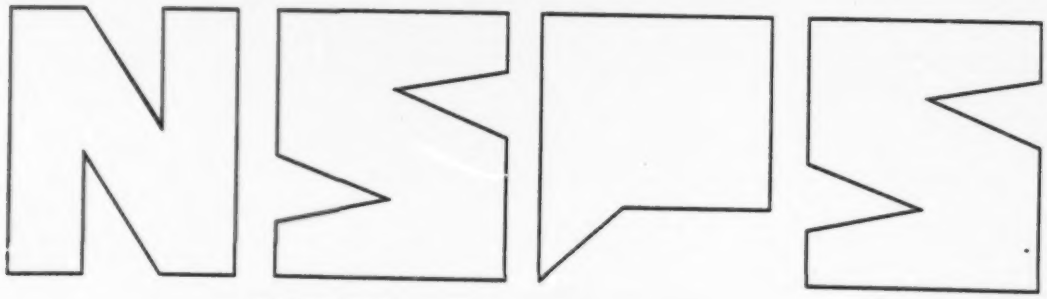

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This report provides a summary of the technical data used in developing proposed new source performance standards (NSPS) for small industrial-commercial-institutional steam generating units (small boilers). The report focuses on nitrogen oxides (NO_x) emissions from boilers firing coal, oil, and gas with heat input capacities of 100 million Btu/hour or less. Conclusions are drawn from the data regarding the performance of technologies available to reduce NO_x emissions. Alternative control levels are then chosen based on the conclusions drawn from the data.

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OVERVIEW OF THE REGULATORY BASELINE, TECHNICAL BASIS, AND ALTERNATIVE CONTROL LEVELS FOR NITROGEN OXIDES (NO_x) EMISSION STANDARDS FOR SMALL STEAM GENERATING UNITS

Emission Standards Division

U.S. Environmental Protection Agency
Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, N.C. 27711

May 1989

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1.0 INTRODUCTION

This report provides an overview of the emission data and technical basis for nitrogen oxides (NO_x) new source performance standards (NSPS) for small boilers. Small boilers are defined as industrial-commercial-institutional steam generating units having a heat input capacity of 29 MW (100 million Btu/hour) or less.

A number of NO_x control techniques were considered for the purpose of evaluating alternative NO_x emission standards for small boilers. Detailed discussions of the design and operating principles of each of these control techniques can be found in: Technology Assessment Report For Industrial Boiler Applications: NO_x Combustion Modification (i.e., NO_x ITAR).[1]

This report is organized according to the major fossil fuel types combusted in small boilers. A summary of key assumptions and conclusions is presented in Section 2.0. Available NO_x emissions data and the results of the technical analyses for natural gas-fired boilers are presented in Section 3.0. Sections 4.0, 5.0, and 6.0 contain similar discussions for distillate oil, residual oil, and coal combustion, respectively.

2.0 SUMMARY

Only a small number of State and local agencies currently regulate NO_x emissions from small boilers.[2] Consequently, the regulatory baseline emission level for small boilers is represented by NO_x emissions from boilers operating without any NO_x controls.

Available NO_x test data on small boilers show that NO_x emissions vary considerably for these boilers operating with or without NO_x control. However, in many cases, these data are insufficient to analyze or explain the reasons for this variability. Where sufficient data were available, regression analysis was employed to develop equations predicting NO_x emissions as a function of key operating parameters affecting NO_x emissions (e.g., boiler load, excess O_2 level, combustion air temperature, and fuel-bound nitrogen content). These regression equations, however, do not explain the high degree of scatter in the data and, as a result, do not predict NO_x emissions with any degree of accuracy. Consequently, neither controlled nor uncontrolled NO_x emission levels can be determined for small boilers. As a result, an insufficient technical basis is available for developing an NSPS.

3.0 NATURAL GAS NO_x EMISSIONS AND CONTROL TECHNIQUES

The NO_x control techniques for which data are available include low excess air (LEA), flue gas recirculation (FGR), overfire air ports (OFA), and staged combustion burners (SCBs). These controls represent the techniques considered to be both commercially available and applicable to small boilers. Two other NO_x control techniques having limited applicability to small boilers are selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR or ammonia injection). These technologies have been applied to some small boilers operating in California to meet stringent NO_x emission limits in that State. Cost analyses, however, indicate that both SCR and SNCR technologies are expensive control options for small boilers (i.e., in excess of $4,000/ton).[3,4] Thus, these two technologies were not considered further.

3.1 REGULATORY BASELINE EMISSION LEVELS

The regulatory baseline is defined as the uncontrolled NO_x emission level because of the virtual absence of State and local regulation of NO_x emissions from small natural gas-fired boilers. Regulatory baseline NO_x emission data from tests conducted on 14 small natural gas-fired boilers ranging in heat input capacity from 2.3 to 26 MW (8 to 88 million Btu/hour) can be found in Table 3-1. In addition to the NO_x emission data, this table presents boiler data for each boiler tested.

As shown by this table, baseline NO_x emissions from these boilers were highly scattered, ranging from 30.5 to 132 ng/J (0.071 to 0.307 lb/million Btu). In an attempt to reduce this scatter, regression analysis was employed to explain the variability in NO_x emissions as a function of boiler load (i.e., heat release rate), excess O_2 level, and combustion air temperature.[7] To evaluate the adequacy of these regression equations for predicting NO_x emissions from small boilers, the actual baseline NO_x emission data in Table 3-1 were compared to the baseline NO_x emissions predicted by the regression equations. This comparison of actual and predicted baseline NO_x emission values is presented in Table 3-2.

TABLE 3-1. NO_x EMISSION DATA ON NATURAL GAS-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS AT BASELINE AND LOW EXCESS AIR CONDITIONS

Boiler Data				Test Data							
Boiler I.D.	Boiler type[a]	Full load heat release rate, kJ/m²-sec (10^3 Btu/ft²-hr)	Boiler capacity, MW (10^6 Btu/hr) heat input	Average test load, percent	Stack O_2, percent baseline/controlled	Combustion air temperature, °C (°F)	NO_x emissions, lb/10^6 Btu baseline/controlled[b]	NOx reduction, percent	CO emissions, ppm @ 3% O_2 baseline/controlled	Boiler efficiency, percent baseline/control	Reference[f]
3-2	FT	479 (152)	3.8 (13)	50	8.0/3.6	Amb[c]	0.122/0.080	34	13/0	NR/84	5
4-4	FT	743 (236)	7.3 (25)	70	6.8/4.8	Amb	0.132/0.111	16	NR/NR[e]	80/NR	5
5-248-1	FT	479 (152)	2.9 (10)	80	11.0/5.5	Amb	0.076/0.072	5	0/145	NR/NR	5
26-1	FT	340 (108)	6.7 (23)	96	7.2/2.7	Amb	0.074/0.093	(31)[d]	15/59	82/84	5
Site 6	FT	NR (NR)	2.3 (8)	33	8.3/7.2	Amb	0.105/0.072	31	28/117	NR/NR	6
1-1	WT, PKG	214 (68)	11 (36)	80	4.5/1.9	Amb	0.101/0.079	22	6/114	NR/NR	5
1-2	WT, PKG	214 (68)	11 (36)	59	4.7/2.2	Amb	0.101/0.095	6	10/67	NR/79	5
1-3	WT, PKG	230 (73)	11 (38)	80	4.5/2.7	Amb	0.117/0.094	19	0/0	78/79	5
5-716-3	WT, PKG	NR (NR)	9.1 (31)	65	5.8/4.1	Amb	0.097/0.079	19	0/0	NR/NR	5
10-4	WT, PKG	290 (92)	22 (75)	82	5.2/3.9	Amb	0.127/0.132	(4)[d]	0/42	80/NR	5
19-2	WT, PKG	211 (67)	6.5 (22)	93	3.2/2.0	Amb	0.075/0.066	12	10/71	80/NR	5
9-EC-1	WT, PKG	221 (70)	22 (75)	79	3.3/2.6	204 (400)	0.307/0.294	4	0/20	NR/79	5
28-1	WT, PKG	246 (78)	26 (88)	41	5.7/3.7	168 (335)	0.257/0.202	21	0/21	83/85	5
38-2	WT, PKG	265 (84)	16 (56)	89	3.2/1.9	288 (550)	0.268/0.222	17	0/0	81/82	5

[a] FT = firetube; WT = watertube; and PKG = packaged.

[b] NO_x emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours) except at Site 6. 30-day tests were performed on the boiler at Site 6. To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.

[c] Amb = ambient temperature [assume 27°C (80°F)].

[d] Numbers in parenthesis indicate a NO_x emission increase from baseline using LEA.

[e] NR = not reported.

[f] Test results from Reference 5 also reported in Reference 1.

TABLE 3-2. COMPARISON OF ACTUAL AND PREDICTED NO_x EMISSIONS FOR UNCONTROLLED NATURAL GAS-FIRED SMALL BOILERS

Boiler I.D.	NO_x emissions (lb/million Btu)		Percent deviation[a]
	Actual	Predicted	
3-2	0.122	0.151	-24
4-4	0.132	0.178	-35
5-248-1	0.076	0.177	-133
26-1	0.071	0.161	-126
1-1	0.101	0.128	-27
1-2	0.101	0.120	-19
1-3	0.117	0.131	-12
10-4	0.127	0.142	-12
19-2	0.075	0.127	-69
9-BC-1	0.307	0.204	33
28-1	0.257	0.178	31
38-2	0.268	0.261	3

[a]Percent deviation = (actual - predicted NO_x emissions) * 100/actual NO_x emissions.

As shown in Table 3-2, the deviation between the actual and the predicted baseline NO_x emission levels ranges from 33 to -133 percent. These large deviations indicate that, even after the regression equations are employed, a great deal of scatter remains. As a result, these regression equations cannot be used to predict baseline NO_x emissions from small natural gas-fired boilers with any degree of accuracy. Consequently, it is not possible to establish a NO_x emission level representative of small natural gas-fired boilers under baseline (i.e., uncontrolled) conditions.

3.2 LOW EXCESS AIR (LEA)

With LEA, the combustion air flow to the boiler is reduced to near the minimum amount needed for complete combustion. The level to which the excess air can be lowered is usually limited by the onset of excessive carbon monoxide (CO) and smoke formation due to incomplete combustion. As discussed in the NO_x ITAR, LEA primarily reduces thermal NO_x emissions.[8] For this reason, LEA is most effective in reducing NO_x emissions from the combustion of low nitrogen bearing fuels such as natural gas and distillate oil.

Two general approaches are used for LEA control. One uses an O_2 trim system on a conventional burner/boiler unit; the other uses an LEA-designed burner along with an O_2 trim device. Natural gas-fired boilers can typically operate using either LEA control system at excess air levels near 10 percent (2 percent O_2 in the flue gas) while maintaining safe boiler operation and satisfactory combustion conditions.

Low excess air controls can be applied to all small boilers equipped with forced draft burners. For boilers equipped with atmospheric burners, LEA cannot be used since excess air levels cannot be controlled; boilers containing these burners are typically cast-iron units. However, some larger cast-iron boilers can be equipped with forced draft burners and, therefore, could use the LEA control technique.

Emission test data from application of LEA control on small natural gas-fired boilers may also be found in Table 3-1 for the same 14 small natural gas-fired boilers discussed in Section 3.1. Like the uncontrolled NO_x emission data, LEA-controlled NO_x emissions from these boilers were

highly scattered, ranging from 28.4 to 126 ng/J (0.066 to 0.294 lb/million Btu). The negative NO_x reductions for two boilers presented in Table 3-1 indicate the LEA-controlled NO_x emissions for these two units were actually higher than the uncontrolled NO_x emissions.

Regression analysis was employed to explain the variability introduced into these data by operation of these boilers under different conditions. A comparison of actual and predicted NO_x emissions using the regression equations developed for this analysis is presented in Table 3-3. As shown in the table, the deviation between the actual and predicted NO_x emissions ranges from 33 to -123 percent. As explained above, these large deviations between the actual and predicted NO_x emission levels indicate that the regression equations are not reliable predictors of LEA-controlled NO_x emissions from these boilers. As a result, it is not possible to establish NO_x emission levels representative of LEA-controlled small natural gas-fired boilers, nor is it possible to predict the NO_x reduction performance of LEA on these boilers.

3.3 OTHER NO_x CONTROLS

3.3.1 Flue Gas Recirculation (FGR)

In an FGR system, a portion of the flue gas is recycled from the stack to the burner windbox. Upon entering the windbox, the gas is mixed with the combustion air prior to being fed to the burner. For this reason, FGR has been applied primarily to boilers firing low nitrogen bearing fuels (i.e., natural gas and distillate oil).

Flue gas recirculation systems are commercially available for small boilers ranging between 1.5 and 29 MW (5 and 100 million Btu/hour) heat input capacity, although no FGR systems have been installed to date on cast-iron boilers.

Table 3-4 presents NO_x emissions data from nine short-term tests conducted on five natural gas-fired boilers, operating both with and without FGR, ranging from 6.5 to 16 MW (22 to 56 million Btu/hour) heat input capacity. This table also provides boiler data for each boiler tested.

TABLE 3-3. COMPARISON OF ACTUAL AND PREDICTED NO_x EMISSIONS FOR THE NATURAL GAS-FIRED SMALL BOILERS USING LEA

Boiler I.D.	NO_x emissions (lb/million Btu)		Percent deviation[a]
	Actual	Predicted	
3-2	0.080	0.135	-69
4-4	0.111	0.169	-53
5-248-1	0.072	0.161	-123
26-1	0.093	0.140	-50
1-1	0.079	0.114	-44
1-2	0.095	0.108	-14
1-3	0.094	0.122	-29
10-4	0.132	0.136	-3
19-2	0.066	0.119	-80
9-BC-1	0.294	0.197	33
28-1	0.202	0.167	17
38-2	0.222	0.242	-9

[a]Percent deviation = (actual - predicted NO_x emissions) * 100/actual NO_x emissions.

TABLE 3-4. NO_x EMISSION DATA ON SMALL NATURAL GAS-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) HEAT INPUT OR LESS OPERATING WITH AND WITHOUT FLUE GAS RECIRCULATION (FGR)

Boiler Data				Test Data							
Boiler I.D.	Boiler type[a]	Full load heat release rate, kJ/m^2-sec (10^3 Btu/ft^2-hr)	Boiler capacity, 10^6 Btu/hr heat input	Percent FGR[c]	Average test load, percent	Stack O_2, percent baseline/controlled	Combustion air temperature, °F	NO_x emissions, $lb/10^6$ Btu baseline/controlled[e]	NO_x reduction, percent	CO emissions, ppm @ 3% O_2 baseline/controlled	Boiler efficiency, percent baseline/controlled	Reference[f]
#3	WT, PKG	NR (NR)	13 (43)	12	93	2.1/2.0	Amb[d]	0.102/0.036	65	0/57	84/84	10,11
#5	WT, PKG	299 (95)	16 (56)	16	60	3.6/3.1	Amb	0.078/0.027	65	182/85	NR/NR	12
[b] #6	WT, PKG	287 (91)	13 (45)	10	100	2.3/1.7	Amb	0.079/0.040	49	NR/NR	84/84	10,13
#6	WT, PKG	287 (91)	13 (45)	14	100	2.3/1.5	Amb	0.079/0.030	62	NR/NR	84/84	10,13
[ECCC	WT, PKG	NR (NR)	9.1 (31)	22	39	3.1/2.6	Amb	0.056/0.022	61	20/20	NR/NR	14
ECCC	WT, PKG	NR (NR)	9.1 (31)	26	30	3.5/1.2	Amb	0.069/0.016	77	10/55	NR/NR	14
[Loc.19	WT, PKG	211 (67)	6.5 (22)	17	79	3.2/3.3	Amb	0.110/0.032	71	19/16	78/79	15
Loc.19	WT, PKG	211 (67)	6.5 (22)	20	80	3.2/3.2	Amb	0.110/0.029	74	19/20	78/79	15
Loc.19	WT, PKG	211 (67)	6.5 (22)	20	83	3.2/2.5	Amb	0.110/0.027	75	19/16	78/78	15

[a] WT = watertube; PKG = packaged.

[b] Brackets indicate that tests were conducted on same boiler but at different operating conditions.

[c] Mass percent of flue gas recirculated to boiler.

[d] NR = not reported; and Amb = ambient temperature [assume 27°C (80°F)].

[e] NO_x emissions were measured by Thermo Electron Chemiluminescent analyzer; all tests were short-term (<3 hours). To convert to ng/J, multiply emissions in $lb/10^6$ Btu by 430.

[f] Test results from References 14 and 15 are also presented in Reference 1.

Table 3-4 shows that the five boilers were operated at a variety of loads and excess O_2 levels and that they have varying amounts of flue gas recirculated to the boiler. This resulted in NO_x emission reductions ranging from 49 to 75 percent and FGR-controlled NO_x emissions ranging from 6.9 to 17 ng/J (0.016 to 0.040 lb/million Btu). Regression analysis, employed to explain the variability in these data by operation of these boilers under different conditions was unsuccessful. Thus, it was not possible to develop equations from these data to predict NO_x emissions from small natural gas-fired boilers using FGR. Further, it is not possible to establish NO_x emission levels representative of small natural gas-fired boilers using FGR, nor is it possible to predict the NO_x reduction performance of FGR on these boilers.

3.3.2 Overfire Air Ports (OFA)

With OFA, conventional burners are used to introduce the fuel and sub-stoichiometric quantities of combustion air (known as primary air) into the boiler. The remaining combustion air (known as secondary air) is introduced downstream of the burners approximately one-third of the length of the furnace through overfire air ports. As discussed in the NO_x ITAR, both thermal and fuel NO_x emissions are reduced using this technique.[1] For this reason, this technique is effective in reducing NO_x emissions from boilers firing any fossil fuel.

Overfire air systems are commercially available for boilers with heat input capacities greater than about 7.3 MW (25 million Btu/hour); they are generally not commercially available for smaller size boilers.

Table 3-5 presents NO_x emissions data from short-term NO_x tests conducted on three small natural gas-fired boilers operating with and without OFA systems. These boilers, rated from 6.5 to 16 MW (22 to 56 million Btu/hour) heat input capacity, operated at different loads and excess O_2 levels. OFA-controlled NO_x emissions ranged from 31 to 61 ng/J (0.073 to 0.142 lb/million Btu) and the NO_x emission reduction achieved by OFA ranged from 13 to 31 percent for the three boilers.

Such a limited data base does not permit regression analysis to be used to develop equations predicting NO_x emissions. Consequently, it is not

TABLE 3-5. NO_x EMISSION DATA FROM NATURAL GAS-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS OPERATING WITH AND WITHOUT OVERFIRE AIR PORTS (OFA)

Boiler Data				Test Data							
Boiler I.D.	Boiler type[a]	Full load heat release rate, kJ/m^2-sec (10^3 Btu/ft^2-hr)	Boiler capacity, MW (10^6 Btu/hr) heat input	Average test load, percent	Stack O_2, percent baseline/controlled	Combustion air temperature, °C (°F)	NO_x emissions, lb/10^6 Btu baseline/controlled[b]	NO_x reduction, percent	CO emissions, ppm @ 3% O_2 baseline/controlled	Boiler efficiency, percent baseline/controlled	Reference[e]
19-2	WT, PKG	211 (67)	6.5 (22)	83	3.2/1.5	Amb[c]	0.084/0.073	13	0/185	NR/NR	5
38-2	WT, PKG	265 (84)	16 (56)	89	1.9/3.2	NR[c]	0.268/0.073	73	0/28	82/80	5
Loc. 38	WT, PKG	265 (84)	16 (56)	88	1.6/3.2	NR	0.206[d]/0.142[d]	31	140/122	81/81	15

[a] WT = watertube; PKG = packaged.

[b] NO_x emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.

[c] Amb = ambient temperature [assume 27°C (80°F)]; NR = not reported.

[d] Estimate only, only NO_x values assume NO_2 is 5% of the total (only NO was measured).

[e] Test results from References 5 and 15 are also presented in Reference 1.

possible to establish NO_x emission levels representative of small natural gas-fired boilers using OFA, nor is it possible to predict the NO_x reduction performance of OFA on these boilers.

3.3.3 Staged Combustion Burners (SCBs)

As the name implies, staged combustion burners, also known as "low NO_x burners," reduce NO_x formation by allowing combustion in stages. The staging technique is similar to that of the OFA system except that the combustion staging is achieved by the burner rather than through the use of OFA ports. One type of SCB stages the fuel, others stage the combustion air to achieve staged combustion.[16] The NO_x ITAR describes the various types of SCBs available for small boilers.[17] As with OFA, both thermal and fuel NO_x emissions are reduced using SCBs. For this reason, this technique is effective in reducing NO_x emissions from boilers firing any fossil fuel.

Staged combustion burners are commercially available in the small boiler size category for boilers with heat input capacities greater than 7.3 MW (25 million Btu/hour). Another type of SCB, called the radiant or ceramic fiber burner, emits low NO_x emissions by combusting gaseous fuels without flame. Ceramic fiber burners for very small natural gas-fired firetube boilers are currently available at the 1.5 MW (5 million Btu/hour) size or less.[18]

Table 3-6 presents NO_x emission data from short-term tests conducted on three natural gas-fired boilers using SCBs, rated between 18 and 31 MW (63 to 106 million Btu/hour) heat input capacity. Nitrogen oxides emissions ranged from 30 to 39 ng/J (0.07 to 0.09 lb/million Btu). Baseline test data were not available for these boilers without combustion staging. Consequently, the reduction in NO_x emissions achieved by SCBs on each of those boilers cannot be determined. As mentioned above for OFA, such a limited data base does not permit the use of regression analysis. Thus, equations predicting NO_x emissions from small natural gas-fired boilers using SCBs could not be developed. Further, it is not possible to establish NO_x emission levels representative of small natural gas-fired boilers using SCBs, nor is it possible to predict the NO_x reduction performance of SCBs on these boilers.

TABLE 3-6. NO_x EMISSION DATA FROM NATURAL GAS-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS USING STAGED COMBUSTION BURNERS (SCB)

Boiler Data				Test Data						
Boiler I.D.	Boiler type[a]	Full load heat release rate kJ/m²-sec (10^3 Btu/ft²-hr)	Boiler capacity, MW (10^6 Btu/hr) heat input	Average test load, percent	Stack O_2, percent baseline/controlled	Combustion air temperature, °C (°F)	NO_x emissions, lb/10^6 Btu baseline/controlled[b]	CO emissions, ppm @ 3% O_2 baseline/controlled	Boiler efficiency, percent baseline/controlled	Reference
CA	WT, PKG	NR (NR)	18 (63)	40	NA[c]/4.0	Amb[c]	NA/0.090	NA/NR[c]	NR/NR	19
#3	WT, PKG	227 (72)	22 (75)	86	NA/4.3	Amb	NA/0.070	NA/744[d]	NA/NR	20
Site 5	WT, PKG	NR (NR)	31 (106)	44	NA/5.8	Amb	NA/0.089	NA/82	NA/NR	21

[a] WT = watertube; PKG = packaged.

[b] NO_x emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (≤3 hours) except for Site 5. Thirty nine day continuous emissions testing was performed at Site 5. To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.

[c] NA = not available; Amb = ambient temperature [assume 27°C (80°F)]; NR = not reported.

[d] This test was demonstrated intentionally at the lowest possible NO_x emissions for this boiler. However, this CO emissions level met the CO regulation of the county's air pollution control district.

4.0 DISTILLATE OIL NO_x EMISSIONS AND CONTROL TECHNIQUES

The NO_x controls for which emission data are available include LEA, FGR, OFA, and SCBs. The operating principles, applicability, and commercial availability of these techniques for distillate oil-fired boilers are the same as for natural gas-fired boilers discussed above.

4.1 REGULATORY BASELINE EMISSION LEVELS

The regulatory baseline is defined as the uncontrolled NO_x emission level because of the virtual absence of State and local regulation of NO_x emissions from small oil-fired boilers. Regulatory baseline NO_x emission data from tests conducted on six small distillate oil-fired boilers, ranging in heat input capacity from 3.8 to 11 MW (13 to 38 million Btu/hour), can be found in Table 4-1. Emission data were collected from one boiler using three different oil atomization techniques. Table 4-1 also presents boiler data for each boiler tested.

Table 4-1 shows that uncontrolled NO_x emissions from the boilers were highly scattered, ranging from 42.1 to 96.3 ng/J (0.098 to 0.224 lb/million Btu). In an attempt to reduce this scatter in the data, regression analysis was employed to explain the variability in NO_x emissions as a function of boiler load (i.e., heat release rate), excess O_2 level, combustion air temperature, and nitrogen content of the oil.[22] The boilers at sites #3-2 and #4-4 were deleted from the analysis due to lack of data on fuel nitrogen content.

A comparison of actual NO_x emissions and predicted NO_x emissions using the regression equations developed from this analysis is presented in Table 4-2. As shown in the table, the deviation between the actual and the predicted NO_x emissions ranges from 26 to -47 percent. These large deviations indicate that, even after the regression equations are employed, a great deal of scatter remains in the data. As a result, these regression equations cannot be used to predict NO_x emissions from these boilers with any degree of accuracy. Further, it is not possible to establish a regulatory baseline NO_x emission level representative of small distillate oil-fired boilers.

TABLE 4-1. NO_x EMISSIONS DATA FROM DISTILLATE OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS AT BASELINE AND LOW EXCESS AIR CONDITIONS

Boiler Data					Test Data								
Boiler I.D	Boiler type[b]	Full load heat release rate, kJ/m²-sec (10³ Btu/ft²-hr)	Boiler capacity, 10⁶ Btu/hr heat input	Fuel nitrogen, percent	Average test load, percent	Stack O_2, percent baseline/controlled	Combustion air temperature, °C (°F)	NO_x emissions,[c] lb/10⁶ Btu baseline/controlled[c]	NO_x reduction, percent	CO emissions, ppm @ 3% O_2 baseline/controlled	PM emissions,[c] lb/10⁶ Btu baseline controlled[c]	Boiler efficiency, percent baseline/controlled	Reference[f]
1-2	FT	479 (152)	3.8 (13)	NA[d]	50	5.6/5.6	Amb[d]	0.221/0.197	11	0/0[d]	0.04/NR	NR/84	5
4-4	FT	743 (236)	7.3 (25)	NA	47	5.2/2.7	Amb	0.224/0.186	17	NR/NR	0.03/NR	85/NR	5
1-3	WT, PKG	214 (68)	11 (36)	0.045	50	8.2/5.1	Amb	0.136/0.118	13	NR/NR	NR/NR	NR/NR	5
19-1 (Steam)[a]	WT, PKG	211 (67)	6.4 (22)	0.004	80	4.3/3.6	Amb	0.090/0.088	18	0/49	NR/0.04	NR/85	5
19-1 (Air)[a]	WT, PKG	211 (67)	6.4 (22)	0.004	80	4.5/2.5	Amb	0.134/0.125	7	0/0	NR/NR	84/NR	5
19-1 (Mech)[a]	WT, PKG	211 (67)	6.4 (22)	0.004	66	6.3/3.7	Amb	0.107/0.103	2	0/0	NR/NR	NR/86	5
Loc. 19	WT, PKG	211 (67)	6.4 (22)	0.004	83	3.2/1.1	Amb	0.134/0.123	19	4/181	0.06/0.04	82/83	15
1-3	WT, PKG	230 (73)	11 (38)	0.045	79	5.9/2.8	177 (350)	0.158/0.134	15	0/17	0.4/NR	81/83	5

[a] Emission tests were conducted on the same boiler operating with three types of oil atomization (i.e., steam, air, and mechanical).

[b] FT = firetube; WT = watertube; PKG = package.

[c] NO_x emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/10⁶ Btu by 430.

[d] NA = not available; NR = not reported; Amb = ambient temperature [assume 27°C (80°F)].

[e] To convert to ng/J, multiply emissions in lb/10⁶ Btu by 430.

[f] Test results from References 5 and 15 are also presented in Reference 1.

TABLE 4-2. COMPARISON OF ACTUAL AND PREDICTED NO_x EMISSIONS FOR UNCONTROLLED DISTILLATE OIL-FIRED SMALL BOILERS

Boiler I.D.	NO_x emissions (lb/million Btu)		Percent deviation[b]
	Actual	Predicted	
1-2	0.136	0.161	-18
19-1 (Steam)[a]	0.098	0.126	-29
19-1 (Air)[a]	0.134	0.126	6
19-1 (Mech)[a]	0.107	0.130	-22
Loc. 19	0.154	0.114	26
1-3	0.158	0.232	-47

[a]Indicates type of oil atomization. Mech = mechanical.

[b]Percent deviation = (actual - predicted NO_x emissions) * 100/actual NO_x emissions.

4.2 LOW EXCESS AIR (LEA)

Emission test data from application of LEA control on small distillate oil-fired boilers may also be found in Table 4-1 for the same six small distillate oil-fired boilers discussed in Section 4.1. Like the uncontrolled NO_x emission data, LEA-controlled NO_x emissions were highly scattered, ranging from 37.8 to 84.7 ng/J (0.088 to 0.197 lb/million Btu). The NO_x emission reductions also varied considerably (from 2 to 19 percent).

As with the uncontrolled NO_x emission data, regression analysis was employed to explain the variability introduced into the data by operation of these boilers under different conditions.[23] A comparison of actual NO_x emissions and predicted NO_x emissions using the regression equations developed from this analysis is summarized in Table 4-3. As shown in the table, the deviation between the actual and the predicted NO_x emissions ranges from 36 to -40 percent. These large deviations between the actual and predicted NO_x emissions indicate that the regression equations are not reliable predictors of LEA-controlled emissions from these boilers. As a result, it is not possible to establish NO_x emission levels which are representative of small distillate oil-fired boilers using LEA, nor is it possible to predict the NO_x reduction performance of LEA on these boilers.

4.3 OTHER NO_x CONTROLS

4.3.1 Flue Gas Recirculation (FGR)

Nitrogen oxides emissions data from tests conducted on two distillate oil-fired boilers operating with and without FGR are summarized in Table 4-4. One boiler was rated at 7.3 MW (25 million Btu/hour) heat input capacity and the other boiler was rated at 16.4 MW (56 million Btu/hour) heat input capacity. This table also provides boiler data for each boiler tested.

Table 4-4 shows that the two boilers were operated at different loads and excess O_2 levels and that they have different amounts of flue gas recirculated to the boilers. This resulted in FGR-controlled NO_x emissions ranging from 17.6 to 65.4 ng/J (0.041 to 0.152 lb/million Btu). Such a

TABLE 4-3. COMPARISON OF ACTUAL AND PREDICTED NO_x EMISSIONS FOR THE DISTILLATE OIL-FIRED SMALL BOILERS USING LEA

Boiler I.D.	NO_x emissions (lb/million Btu)		Percent deviation[b]
	Actual	Predicted	
1-2	0.118	0.142	-20
19-1 (Steam)[a]	0.088	0.119	-35
19-1 (Air)[a]	0.125	0.106	16
19-1 (Mech)[a]	0.105	0.110	-5
Loc. 19	0.125	0.080	36
1-3	0.134	0.187	-40

[a]Indicates type of oil atomization. Mech = mechanical.

[b]Percent deviation = (actual - predicted NO_x emissions) * 100/actual NO_x emissions.

TABLE 4-4. NO_x EMISSIONS DATA FROM DISTILLATE OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) HEAT INPUT OR LESS OPERATING WITH AND WITHOUT FLUE GAS RECIRCULATION (FGR)

Boiler Data					Test Data									
Boiler I.D.	Boiler type[a]	Full load heat release rate, kJ/m^3-sec (10^3 Btu/ft^3-hr)	Boiler capacity, MW (10^6 Btu/hr) heat input	Fuel nitrogen, percent	Percent FGR[b]	Average test load, percent	Stack O_2, percent baseline/controlled	Combustion air temperature, °F	NO_x emissions, lb/10^6 Btu baseline/controlled[c]	NO_x reduction, percent	CO emissions, ppm @ 3% O_2 baseline/controlled	PM emissions, lb/10^6 Btu baseline/controlled[c]	Boiler efficiency percent baseline/controlled	Reference[f]
85	WT, PKG	299 (95)	16 (56)	NA[d]	10	100	3.5/3.4	Amb[d]	0.185/0.152	18	20/24	NR/NR[d]	NR/NR	12
Loc. 19	WT, PKG	211 (67)	6.5 (22)	0.004	28	85	3.2/0.8	Amb	0.154/0.041	73	4/46	0.04/0.01	82/82	15

[a] WT = watertube; PKG = packaged.

[b] Percent of flue gas mass recirculated to boiler.

[c] NO_x emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.

[d] NA = not available; Amb = ambient temperature [assume 27°C (80°F)]; NR = not reported.

[e] To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.

[f] Test results from Reference 15 are also presented in Reference 1.

limited data base does not permit the use of regression analysis to develop equations predicting NO_x emissions from small distillate oil-fired boilers using FGR. Consequently, it is not possible to establish NO_x emission levels representative of small distillate oil-fired boilers using FGR, nor is it possible to predict the NO_x reduction performance of FGR on these boilers.

4.3.2 Overfire Air Ports (OFA)

Table 4-5 presents NO_x emission data from tests conducted on one small distillate oil-fired boiler operating with and without OFA and rated at 6.5 MW (22 million Btu/hour) heat input capacity. This table also provides boiler data for this boiler. This boiler emitted 53.8 ng/J (0.125 lb/million Btu) of NO_x during OFA operation and 66.2 ng/J (0.154 lb/million Btu) of NO_x during baseline testing, resulting in a 19 percent reduction in NO_x emissions over baseline. As mentioned above for FGR, such a limited data base does not permit the use of regression analysis. Thus, equations predicting NO_x emissions and NO_x emission reductions from small distillate oil-fired boilers using OFA cannot be developed. Further, it is not possible to establish NO_x emission levels representative of small distillate oil-fired boilers using OFA, nor is it possible to predict the NO_x emission reduction performance of OFA on these boilers.

4.3.3 Staged Combustion Burners (SCBs)

The results of a single NO_x test on one small distillate oil-fired boiler rated at 22 MW (75 million Btu/hour) heat input capacity using a staged combustion burner are presented in Table 4-6. Emissions of NO_x measured from this boiler were 47.3 ng/J (0.110 lb/million Btu) during low NO_x operation. Baseline test data were not available for this boiler operating without combustion staging. Consequently, the reduction in NO_x emissions achieved by SCBs on this boiler cannot be determined. As mentioned above for both FGR and OFA, such a limited data base does not permit the use of regression analysis. Thus, equations predicting NO_x emissions from small distillate oil-fired boilers using SCBs could not be developed. As a result,

TABLE 4-5. NO_x EMISSIONS DATA FROM DISTILLATE OIL-FIRED STEAM GENERATORS RATED AT 29 MJ (100 MILLION BTU/HOUR) HEAT INPUT OR LESS OPERATING WITH AND WITHOUT OVERFIRE AIR PORTS (OFA)

Boiler Data					Test Data								
Boiler I.D.	Boiler type[a]	Full load heat release rate, kJ/m^2-sec (10^3 Btu/ft^2-hr)	Boiler capacity, MW (10^6 Btu/hr) heat input	Fuel nitrogen, percent	Average test load, percent	Stack O_2, percent baseline/controlled	Combustion air temperature, °C (°F)	NO_x emissions, lb/10^6 Btu baseline/controlled[b]	NO_x reduction, percent	CO emissions, ppm @ 3% O_2 baseline/controlled	PM emissions, lb/10^6 Btu baseline/controlled[d]	Boiler efficiency, percent baseline/controlled	Reference[e]
Loc. 19	WT, PEG	211 (67)	6.5 (22)	0.004	83	3.2/3.1	Amb[c]	0.154/0.125	19	4/29	0.06/0.03	82/83	15

[a] WT = watertube; PEG = packaged.

[b] NO_x emissions were measured by Thermo Electron Chemiluminescent analyser. All tests were short-term (<3 hours). To convert to ng/J, multiply emi in lb/10^6 Btu by 430.

[c] Amb = ambient temperature (assume 27°C (80°F)).

[d] To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.

[e] Test results from Reference 15 are presented in Reference 1.

TABLE 4-6. NO_x EMISSIONS DATA FROM DISTILLATE OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS USING STAGED COMBUSTION BURNERS (SCB)

Boiler Data				Test Data						
Boiler I.D.	Boiler type[a]	Full load heat release rate, kJ/m^2-sec (10^3 Btu/ft^2-hr)	Boiler capacity, MW (10^6 Btu/hr) heat input	Average test load, percent	Stack O_2, percent baseline/controlled	Combustion air temperature, °F	NO_x emissions, lb/10^6 Btu baseline/controlled[b]	CO emissions, ppm @ 3% O_2 baseline/controlled	Boiler efficiency, percent baseline/controlled	Reference
#3	WT, PKG	227 (72)	22 (75)	84	NA[c]/1.9	Amb[c]	NA/0.110	NA/91	NR/NR[c]	24

[a] WT = watertube; PKG = packaged.

[b] NO_x emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.

[c] NA = not available; Amb = ambient temperature [assume 27°C (80°F)]; NR = not reported.

it is not possible to establish NO_x emission levels representative of small distillate oil-fired boilers using SCBs, nor is it possible to predict the NO_x emission reduction performance of SCBs on these boilers.

5.0 RESIDUAL OIL NO_x EMISSIONS AND CONTROL TECHNIQUES

The NO_x controls for which emission data are available include LEA, FGR, and OFA. No emission data are available for SCBs operating on these boilers. The operating principles, applicability, and commercial availability of these techniques for residual oil-fired boilers are the same as for both natural gas and distillate oil-fired boilers discussed above.

5.1 REGULATORY BASELINE EMISSION LEVELS

The regulatory baseline is defined as the uncontrolled NO_x emission level because of the virtual absence of State and local regulation of NO_x emissions from small residual oil-fired boilers. Regulatory baseline NO_x emission data from tests conducted on 14 residual oil-fired boilers, ranging in heat input capacity from 2.6 to 29 MW (9 to 100 million Btu/hour) can be found in Table 5-1. This table also presents boiler data for each boiler tested.

Table 5-1 shows that uncontrolled NO_x emissions from these boilers were highly scattered, ranging from 86 to 276 ng/J (0.2 to 0.64 lb/million Btu). In an attempt to reduce this scatter, regression analysis was employed to explain the variability in NO_x emissions as a function of boiler load (i.e., heat release rate), excess O_2 level, combustion air temperature, and nitrogen content of the oil.[25] Three boilers (#24-TV, ECCC, and #28-1) were deleted from the analysis because of lack of data on either heat release rate or fuel nitrogen content.

A comparison of actual NO_x emissions in Table 5-1 and predicted NO_x emissions using the NO_x regression equations developed from this analysis is summarized in Table 5-2. As shown, the deviation between actual and the predicted NO_x emissions ranges from 38 to -58 percent. As with other fuels, these large deviations indicate that, even after the regression equations are employed, a great deal of scatter remains in the data. As a result, these regression equations cannot be used to predict NO_x emissions from these boilers with any degree of accuracy. Consequently, it is not possible to establish a baseline, or uncontrolled, NO_x emission level which is representative of small residual oil-fired boilers.

TABLE 5-1. NO_x EMISSIONS DATA FROM RESIDUAL OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS AT BASELINE AND LOW EXCESS AIR CONDITIONS

Boiler Data					Test Data							
Boiler I.D.	Boiler type[b]	Full load heat release rate, kJ/m^3-sec (10^3 Btu/ft^3-hr)	Boiler capacity, 10^6 Btu/hr heat input	Fuel nitrogen, percent	Average test load, percent	Stack O_2, percent baseline/controlled	Combustion air temperature, °C (°F)	NO emissions, lb/10^6 Btu baseline/controlled[c]	NO reduction, percent	CO emissions, ppm @ 3% O_2 baseline/controlled	PM emissions, lb/10^6 Btu baseline/controlled[f]	Boiler efficiency, percent baseline/controlled	Reference[g]
23-1	FT	410 (135)	2.6 (9)	0.27	96	5.4/5.9	Amb[d]	0.389/0.328	16	21/26	NR/47	68/NR	5
24-TV	FT	NR[d] (NR)	3.8 (13)	1.36	104	3.2/1.9	Amb	0.239/0.227	5	0/113	0.09/NR	85/NR	5
26-1	FT	340 (108)	6.7 (23)	0.03	94	6.9/5.8	Amb	0.213/0.201	6	13/21	0.08/NR	86/87	5
2-4	WT, FE	183 (58)	24 (81)	0.38	80	5.7/5.4	Amb	0.641/0.572	11	0/0	NR/NR	NR/81	5
16-2	WT, PEG	183 (85)	24 (81)	0.29	83	4.9/5.7	Amb	0.256/0.236	8	0/0	NR/NR	85/88	5
Loc. 19	WT, PEG	211 (67)	6.5 (22)	0.25	80	2.9/1.6	Amb	0.278/0.193	31	4/185	0.08/0.07	83/84	15
19-1 (Steam)[a]	WT, PEG	211 (67)	6.5 (22)	0.44	83	4.0/2.6	Amb	0.459/0.458	5	0/90	0.03/NR	84/85	5
19-1 (Air)[a]	WT, PEG	211 (67)	6.5 (22)	0.44	83	4.4/2.8	Amb	0.436/0.368	16	0/NR	NR/NR	85/85	5
19-2	WT, PEG	211 (67)	6.5 (22)	0.14	81	3.1/0.9	Amb	0.217/0.159	27	19/58	NR/0.15	0586	5
20-4	WT, PEG	432 (137)	29 (100)	0.37	64	5.7/4.8	Amb	0.398/0.356	11	0/82	0.09/NR	80/NR	5
ECCC	WT, PEG	NR (NR)	9.1 (31)	0.19	78	5.5/3.6	Amb	0.200/0.145	28	<10/<10	NR/NR	NR/NR	14
28-1	WT, PEG	246 (78)	26 (88)	NR	41	5.3/4.9	174 (345)	0.263/0.231	12	0/45	NR/NR	86/87	5
37-2	WT, PEG	318 (101)	15 (50)	0.70	81	4.3/3.8	110 (230)	0.251/0.230	8	0/0	0.14/NR	85/NR	5
Loc. 38	WT, PEG	265 (84)	16 (56)	0.14	85	3.1/0.9	138 (288)	0.388[e]/0.305[e]	21	22/65	0.15/0.11	85/86	15
38-2	WT, PEG	265 (84)	16 (56)	0.49	81	3.0/1.6	157 (315)	0.419/0.312	26	0/120	0.11/NR	87/87	5

[a] Emission tests were conducted on the same boiler operating with two types of oil atomization systems (i.e., steam and air).

[b] FT = firetube; WT = watertube; PEG = packaged; and FE = field erected.

[c] NO emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.

[d] NR = not reported; Amb = ambient temperature [assume 27°C (80°F)].

[e] Estimate only, NO values assume NO_2 is 5% of the total (only NO was measured).

[f] To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.

[g] Test results from References 5, 14, and 15 are also presented in Reference 1.

TABLE 5-2. COMPARISON OF ACTUAL AND PREDICTED NO_x EMISSIONS FOR UNCONTROLLED RESIDUAL OIL-FIRED SMALL BOILERS

Boiler I.D.[a]	NO_x Emissions (lb/million Btu) Actual	Predicted	Percent deviation[b]
23-1	0.389	0.392	-1
26-1	0.213	0.217	-2
2-4	0.641	0.395	38
16-2	0.256	0.355	-39
Loc. 19	0.278	0.290	-4
19-1 (Steam)[a]	0.459	0.429	6
19-1 (Air)[a]	0.436	0.433	1
19-2	0.217	0.217	0
20-4	0.398	0.431	-8
37-2	0.251	0.397	-58
Loc. 38	0.386	0.266	31
38-2	0.419	0.500	-19

[a]Indicates type of oil atomization.

[b]Percent deviation = (actual - predicted NO_x emissions) * 100/actual NO_x emissions.

5.2 LOW EXCESS AIR (LEA)

Emission test data from application of LEA control on small residual oil-fired boilers may also be found in Table 5-1 for the same 14 small residual oil-fired boilers discussed in Section 5-1. Like the uncontrolled NO_x emission data, LEA-controlled NO_x emissions were highly scattered, ranging from 62.4 to 246 ng/J (0.145 to 0.572 lb/million Btu). The NO_x emission reductions also varied considerably (from 5 to 28 percent).

As with the uncontrolled NO_x emission data, regression analysis was employed to explain the variability introduced into the data by operation of these boilers under different conditions.[26] A comparison of actual NO_x emissions and predicted NO_x emissions using the regression equations developed from this analysis is summarized in Table 5-3. As shown in Table 5-3, the deviation between the actual and the predicted NO_x emissions ranges from 35 to -69 percent. As explained above, these large deviations between actual and predicted NO_x emissions indicate that the regression equations are not reliable predictors of LEA-controlled NO_x emissions from these boilers. As a result, it is not possible to establish NO_x emission levels representative of small residual oil-fired boilers using LEA, nor is it possible to predict the NO_x reduction performance of LEA on these boilers.

5.3 OTHER NO_x CONTROLS

5.3.1 Flue Gas Recirculation (FGR)

Nitrogen oxides emissions data from tests conducted on two residual oil-fired watertube boilers, one operating with, and the other without FGR are summarized in Table 5-4. One boiler was rated at 9.1 MW (31 million Btu/hour) heat input capacity while the other boiler was rated at 6.5 MW (22 million Btu/hour) heat input capacity. Table 5-4 also provides boiler data for both boilers.

Table 5-4 shows that the two boilers operated at different loads and excess O_2 levels and that they have varying amounts of flue gas being recirculated to the boilers. This resulted in FGR-controlled NO_x emissions ranging from 48 to 83 ng/J (0.112 to 0.193 lb/million Btu). Such a limited

TABLE 5-3. COMPARISON OF ACTUAL AND PREDICTED NO_x EMISSIONS FOR THE RESIDUAL OIL-FIRED SMALL BOILERS USING LEA

Boiler I.D.[a]	NO_x Emissions (lb/million Btu) Actual	Predicted	Percent deviation[b]
23-1	0.328	0.372	-13
26-1	0.201	0.181	10
2-4	0.572	0.374	35
16-2	0.236	0.342	-45
Loc. 19	0.193	0.270	-40
19-1 (Steam)[a]	0.438	0.413	6
19-1 (Air)[a]	0.368	0.415	-13
19-2	0.159	0.179	-13
20-4	0.356	0.412	-16
37-2	0.230	0.389	-69
Loc. 38	0.305	0.211	31
38-2	0.312	0.469	-50

[a]Indicates type of oil atomization.

[b]Percent deviation = (actual - predicted NO_x emissions) * 100/actual NO_x emissions.

TABLE 5-4. NO_x EMISSION DATA FROM RESIDUAL OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) HEAT INPUT OR LESS OPERATING WITH AND WITHOUT FLUE GAS RECIRCULATION (FGR)

Boiler Data						Test Data								
Boiler I.D.	Boiler type[a]	Full load heat release rate, kJ/m³-sec (10⁴ Btu/ft³-hr)	Boiler capacity, MW (10⁶ Btu/hr) heat input	Fuel nitrogen, percent	Percent FGR[c]	Average test load, percent	Stack O_2, percent baseline/controlled	Combustion air temperature, °C (°F)	NO_x emissions, lb/10⁶ Btu baseline/controlled[d]	NO_x reduction, percent	CO emissions, ppm @ 3% O_2 baseline/controlled[f]	PM emissions, lb/10⁶ Btu baseline/controlled[f]	Boiler efficiency, percent baseline/controlled	Reference[g]
ECCC[b]	WT,PKG	NR[e] (NR)	9.1 (31)	0.19	7	67	4.4/4.5	Amb[e]	0.161/0.157	3	20/20	NR/NR	NR/NR	14
ECCC[b]	WT,PKG	NR (NR)	9.1 (31)	0.19	19	67	4.4/2.0	Amb	0.161/0.112	30	10/145	NR/NR	NR/NR	14
Loc. 19	WT,PKG	211 (67)	6.5 (22)	0.25	25	81	3.1/1.8	Amb	0.278/0.193	31	4/90	0.08/0.08	83/82	15

[a] WT = watertube, PKG = packaged.

[b] Multiple tests were conducted on the same boiler but at different operating conditions.

[c] Percent of flue gas mass recirculated to boiler.

[d] NO_x emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/10⁶ Btu by 430.

[e] NR = not reported; Amb = ambient temperature [assume 27°C (80°F)].

[f] To convert to ng/J, multiply emissions in lb/10⁶ Btu by 430.

[g] Test results from Reference 14 and 15 are also presented in Reference 1.

data base does not permit the use of regression analysis to develop equations predicting NO_x emissions from residual oil-fired small boilers using FGR. Consequently, it is not possible to establish NO_x emission levels representative of small residual oil-fired boilers using FGR, nor is it possible to predict NO_x reduction performance of FGR on these boilers.

5.3.2 Overfire Air Ports (OFA)

Table 5-5 presents NO_x emission data from tests conducted on four small residual oil-fired boilers operating with and without OFA and ranging in heat input capacity from 6.5 to 16 MW (22 to 56 million Btu/hour).

Table 5-5 shows that OFA-controlled NO_x emissions were also highly scattered, ranging from 60.6 to 105 ng/J (0.141 to 0.245 lb/million Btu). Furthermore, reductions in NO_x emissions ranged considerably, from 24 to 47 percent. As mentioned above for FGR, such a limited data base does not permit the use of regression analysis. Thus, equations predicting NO_x emissions and NO_x emission reductions from small residual oil-fired boilers using OFA cannot be developed. Consequently, it is not possible to establish NO_x emission levels representative of small residual oil-fired boilers using OFA, nor is it possible to predict the NO_x emission reduction performance of OFA for these boilers.

TABLE 5-5. NO_x EMISSIONS DATA FROM RESIDUAL OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS OPERATING WITH AND WITHOUT OVERFIRE AIR PORTS (OFA)

Boiler Data					Test Data							
Boiler I.D.	Boiler type[a]	Full load heat release rate, kJ/m^2-sec (10^3 Btu/ft^2-hr)	Boiler capacity, MW (10^6 Btu/hr) heat input	Fuel nitrogen, percent	Average test load, percent	Stack O_2, percent baseline/controlled	Combustion air temperature, °C (°F)	NO_x emissions, lb/10^6 Btu baseline/controlled[c]	NO_x reduction, percent	CO emissions, ppm @ 3% O_2 baseline/controlled	PM emissions, lb/10^6 Btu baseline/controlled[e]	Boiler efficiency, percent baseline/controlled	Reference[f]
19-2[b]	WT,PKG	211 (67)	6.5 (22)	0.14	80	3.1/3.1	Amb[d]	0.217/0.166	24	0/0	0.03/MR[d]	84/82	5
19-2[b]	WT,PKG	211 (67)	6.5 (22)	0.44	80	3.1/2.4	Amb	0.217/0.141	35	0/190	0.03/MR	84/82	5
Loc. 19	WT,PKG	211 (67)	6.5 (22)	0.44	79	3.1/2.4	Amb	0.278/0.194	30	4/24	0.08/0.07	83/83	15
38-2	WT,PKG	265 (84)	16 (56)	0.49	80	3.0/2.9	157 (315)	0.419/0.222	47	0/55	0.11/0.14	87/87	5
Loc. 38	WT,PKG	265 (84)	16 (56)	0.31	85	2.9/3.3	138 (280)	0.386[e]/0.245[e]	37	22/62	0.15/0.12	85/85	15

[a] WT = watertube, PKG = packaged.

[b] Multiple tests were conducted on the same boiler but at different operating conditions.

[c] NO_x emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.

[d] Amb = ambient temperature [assume 27°C (80°F)]; MR = not reported.

[e] Estimate only, NO_x values assume NO_2 is 5% of the total (only NO was measured).

[f] To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.

[g] Test results from Reference 5 and 15 are also presented in Reference 1.

6.0 COAL NO_x EMISSIONS AND CONTROL TECHNIQUES

The NO_x controls for which emission data are available include LEA and OFA. Except where noted, the operating principles, applicability, and commercial availability of these control techniques are the same as those discussed above for natural gas- and oil-fired boilers.

6.1 REGULATORY BASELINE EMISSION LEVELS

The regulatory baseline is defined as the uncontrolled NO_x emission level because of the virtual absence of State and local regulation of NO_x emissions from small coal-fired boilers. Regulatory baseline NO_x emission data from tests conducted on 11 small coal-fired boilers, ranging in heat input capacity from 16 to 29 MW (56 to 100 million Btu/hour), can be found in Table 6-1. Spreader, underfeed, overfeed, and vibrating grate stokers are represented. In addition to presenting NO_x emission data, this table presents data for each boiler tested.

As shown in this table, NO_x emissions from these boilers were highly scattered, ranging from 98 to 273 ng/J (0.229 to 0.635 lb/million Btu). Regression analysis, employed to explain the variability in the data caused by operation of these boilers under different operating conditions (i.e., boiler load, grate heat release rate, excess air level, and fuel moisture and nitrogen contents), was unsuccessful.[33,34] Thus, regression equations relating NO_x emissions from small coal-fired boilers to various boiler operating conditions could not be developed and, as a result, it is not possible to establish an uncontrolled NO_x emission level representative of small coal-fired stoker boilers.

Table 6-2 presents uncontrolled NO_x emission data from tests conducted on three Fluidized Bed Combustion (FBC) boilers, ranging in heat input capacity from 14.7 to 28.4 MW (50 to 97 million Btu/hour). As shown in Table 6-2, NO_x emissions from FBC boilers varied as much as those from the spreader stoker boilers, ranging from 181 to 327 ng/J (0.42 to 0.76 lb/million Btu). Regression analysis, employed to explain the variability in the data caused

TABLE 6-1. NO_x EMISSION DATA FROM COAL-FIRED BOILERS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS AT BASELINE AND LOW EXCESS AIR CONDITIONS[a]

Boiler Data						Test Data						
Boiler I.D.	Boiler type[c]	Full load grate heat release rate, kJ/m^2-sec (10^3 Btu/ft^2-hr)	Boiler capacity, (10^6 Btu/hr) heat input	Moisture in fuel, weight percent	Fuel nitrogen, percent	Average test load, percent	Stack O_2, percent baseline/controlled	NO_x emissions lb/10^6 Btu baseline/controlled[d,g]	NO_x reduction, percent	CO emissions, ppm @ 3% O_2 baseline/controlled	PM emissions[h] lb/10^6 Btu baseline/controlled	Reference[i]
#21-2	SS	1,484 (471)	18 (63)	2.1	1.5	81	8.0/5.8	0.635/0.452	29	35/42	NR/0.55	5
#21-3	SS	1,421 (451)	28 (94)	1.6	1.4	84	7.8/5.5	0.634/0.491	23	122/104	0.24/NR	5
[b] Site G	SS	2,249 (714)	29 (99)	4.3	1.0	99	7.2/5.0	0.540/0.412	24	NR/NR	6.3[h]/NR	27
Site G	SS	2,249 (714)	29 (99)	4.8	1.0	99	7.5/4.0	0.572/0.401	30	NR/NR	4.8[h]/NR	27
Site F	SS	2,167 (688)	29 (98)	3.3	1.2	75	8.9/7.8	0.468/0.443	5	146/137	NR/NR	28
Site F	SS	2,167 (688)	29 (98)	4.7	1.1	75	9.9/6.2	0.454/0.312[f]	31	139/96	NR/NR	28
Fairmont #3	SS	NR (NR)[e]	29 (100)	7.3	1.1	75	8.0/6.5	0.506[f]/0.405[f]	20	47/155	1.8[h]/2.6[h]	29
Fairmont #3	SS	NR (NR)	29 (100)	14.2	0.5	76	8.0/7.0	0.483[f]/0.418[f]	13	83/75	2.8[h]/2.6[h]	29
15-32-10	UFS	1,449 (460)	22 (75)	10.5	1.4	77	6.6/4.9	0.364/0.263	28	0/0	NR/NR	5
15-32-13	UFS	1,449 (460)	22 (75)	10.5	1.4	77	10.3/8.0	0.433/0.361	17	0/0	1.3/NR	5
Site I	OFS	1,188 (377)	28 (95)	3.1	1.8	104	8.3/5.0	0.400/0.283	29	NR/NR	1.0[h]/NR	30
Site I	OFS	1,188 (377)	28 (95)	2.3	1.4	102	7.7/5.9	0.229/0.211	8	NR/NR	1.4[h]/NR	30
Site J	OFS	1,244 (395)	23 (77)	3.1	1.7	100	9.1/7.5	0.353/0.316	10	NR/NR	NR/NR	31
Site K	OFS	1,276 (405)	18 (63)	6.5	1.6	101	7.9/7.0	0.324/0.318	4	139/138	0.71[h]/0.69[h]	32
UW-Stout #2	VGS	NR (NR)	16 (56)	21.5	0.9	57	9.3/5.2	0.277/0.209	25	30/111	0.72/0.56	29

[a] All boilers used no air preheat.
[b] Brackets indicate multiple parametric tests were conducted on each boiler.
[c] SS = spreader stoker; UFS = underfeed stoker; OFS = overfeed stoker; and VGS = vibrating grate stoker.
[d] NO_x emissions were measured by Thermo Electron Chemiluminescent Analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.
[e] NR = not reported.
[f] Estimate only; NO_x values assume NO_2 is 5% of the total (only NO was measured).
[g] To convert to ng/J, multiply emissions in lb/10^6 Btu by 430.
[h] PM emissions were taken from inlet to the PM control device (uncontrolled emissions).
[i] Test results from References 5 and 27 to 30 are also presented in Reference 1.

TABLE 6-2. NO_x EMISSION DATA FROM COAL-FIRED FLUIDIZED BED COMBUSTION (FBC) BOILERS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS AT BASELINE CONDITIONS

Boiler I.D.	Boiler Type[b]	Boiler size, MW (10^6 Btu/hour) heat input	Weight percent nitrogen in coal	Coal moisture, weight percent	Average test load, percent	Stack O_2, percent	NO_x emissions, lb/10^6 Btu[c]	CO emissions, ppm	PM emissions, lb/10^6 Btu[c]	Emission test method (test duration)[d]	Reference
a[A[e]	Pkg. Sb	26.4 (90)	NA[f]	NA	59	6.0[g]	0.76	585	NA	CEM (16)	35
a[A	Pkg. Sb	26.4 (90)	NA	NA	70	6.7[g]	0.42	160	NA	CEM (8)	35
B	Pkg. Bb	28.4 (97)	NA	NA	72	6.7	0.56	NA	0.02	NO_x: EPA-7 (3 hrs) PM: EPA-5 (3 hrs)	36
C	Pkg. Bb	14.7 (50)	1.06	6.4	72	10.5	0.62	453	NA	CEM (7.5)	37,38
C	Pkg. Bb	14.7 (50)	0.97	6.8	66	11.1	0.60	507	NA	CEM (15 hrs)	37,38
C	Pkg. Bb	14.7 (50)	NA	NA	56	11.6	0.70	1,007	NA	CEM (5 hrs)	37,38

[a] Brackets indicate multiple parametric tests were conducted on each boiler.

[b] Pkg. Sb = packaged staged bed; and Pkg. Bb = packaged bubbling bed.

[c] Multiply emissions by 430 to convert to ng/J.

[d] CEM = certified continuous emission monitor; and EPA = EPA reference methods. The number in parenthesis represent the number of days unless otherwise specified.

[e] Excluded emission data on staged combustion test.

[f] NA = not available.

[g] Excess O_2 measured at the inlet of the baghouse.

by operation of these boilers under different conditions, was also unsuccessful. Consequently, it is not possible to establish an uncontrolled NO_x emission level representative of small FBC boilers.

6.2 LOW EXCESS AIR (LEA)

The operating principles of LEA are the same as those discussed in Section 3.2 for natural gas-fired small boilers. For small coal-fired boilers, LEA is achieved by design and adjustment of the combustion air delivery system. Typical stack O_2 levels for small stoker boilers without LEA are about 6 percent O_2 (40 percent excess air) on newer units and about 5 percent O_2 (30 percent excess air) when LEA is applied.[39,40] Small FBC boilers are typically designed to operate at minimum excess O_2 levels ranging from 3 to 4.5 percent O_2 (15 to 25 percent excess air).[41]

Small coal-fired boilers are generally balanced draft units, with both forced draft (FD) and induced draft (ID) fans. Often, these units control combustion air flow based on furnace pressure. The FD fan damper automatically adjusts to changes in furnace pressure, and the ID fan tracks the FD signal. By including an O_2 trim system, better O_2 control can be obtained in the boiler under extreme load variations.

Emission test data from application of LEA control on small coal-fired stoker boilers may also be found in Table 6-1 for the same 11 small coal-fired stoker boilers discussed in Section 6.1. Like the uncontrolled NO_x emission data, LEA-controlled NO_x emissions were highly scattered, ranging from 90 to 211 ng/J (0.209 to 0.491 lb/million Btu). The NO_x emission reduction achieved by LEA also varied substantially, ranging from 4 to 31 percent.

As with the uncontrolled NO_x emission data, regression analysis, employed to explain the variability in the data caused by operation of these boilers under different conditions was unsuccessful. Consequently, it is not possible to establish NO_x emission levels which are representative of small coal-fired stokers using LEA.

Emission data are not available on small coal-fired FBC boilers using LEA. Consequently, NO_x emission levels cannot be established for small FBC boilers using LEA.

6.3 OVERFIRE AIR PORTS (OFA)

The mechanism by which NO_x emissions are reduced using OFA is the same for coal-fired boilers as that discussed earlier for natural gas- and oil-fired boilers. Coal-fired stoker boilers achieve partial staged combustion by the nature of their design. Part of the fuel is combusted on the grate while the rest is burned in suspension above the grate. Combustion air can be split and introduced both below the grate and above the grate through OFA ports. Many stoker boilers have OFA ports as smoke control devices. Therefore, the location of the OFA ports in the boiler may not be at the optimum location to achieve the greatest NO_x reductions.

Nitrogen oxides emissions from FBC boilers can also be reduced further by staging of the combustion air. A substoichiometric amount of air is introduced through the fluidizing air (primary air) injection point. The balance of the air needed to achieve adequate combustion efficiency is added above the bed. This allows combustion to be completed in the freeboard zone (i.e., space between the top of the fluidized bed and boiler outlet).

Performance data on NO_x emissions are not available on small coal-fired stoker boilers using OFA. However, NO_x emission data are available from the FBC boiler at site A reported in Table 6-2 using OFA. During a 2-day OFA test, NO_x emissions averaged 258 ng/J (0.6 lb/million Btu). This compares with average NO_x emissions of 378 ng/J (0.88 lb/million Btu) obtained for this boiler during 2 days of operation without OFA immediately following the staged combustion test.[42]

Because OFA emissions testing was conducted on only one boiler, such a limited data base does not permit the use of regression analysis to develop equations predicting NO_x emissions from small FBC boilers using OFA. Consequently, it is not possible to establish NO_x emission levels representative of small coal-fired boilers using OFA, nor is it possible to predict the NO_x reduction performance of OFA on these boilers.

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